Model-Based Testing with Graph Transformation Systems

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Abstract

Graph Grammars have many structural advantages, which are potential benefits for the model-based testing process.This report describes the setup of a research project where the use of Graph Grammars in model-based testing is researched. The goal of the project is to create a system for automatic test generation from Graph Grammars and to validate this system. A graph transformation tool, GROOVE, and a model-based testing tool, ATM, are used as the backbone of the system. The system will be validated using the results of several case-studies.

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Chapter 1

Introduction

1.1 Introduction

In software development projects, often limited time and resources are available for testing. However, testing is an important part of software development, because it decreases future maintainance costs [?]. Testing is a complex process and should be done often [?]. Therefore, the testing process should be as efficient as possible in order to save resources.

Test automation allows repeated testing during the development process. The advantage of this is that bugs are found early and can therefore be fixed early. A widely used practice is maintaining a *test suite*, which is a collection of tests. However, when the creation of a test suite is done manually, this still leaves room for human error [?]. Also, manual creation of test-cases is not time-efficient.

Creating an abstract representation or a *model* of the system is a way to tackle these problems. What is meant by a model in this report, is the description of the behavior of a system. Models such as state charts and sequence charts, which only describe the system architecture, are not considered here. A model can be used to systematically generate tests for the system. This is referred to as *model-based testing*. This leads to a larger test suite in a shorter amount of time than if done manually. These models are created from the specification documents provided by the end-user. These specification documents are 'notoriously error-prone' [?]. If the tester copies an error in the document or makes a wrong interpretation, the constructed model becomes incorrect.

The stakeholders evaluate the constructed model to verify its correctness. However, the visual or textual representation of large models may become troublesome to understand, which is referred to as the model having a low model transparency. The feedback process of the stakeholders is obstructed by low transparency models. Models that are often used are state machines, i.e. a collection of nodes representing the states of the system connected by transitions representing an action taken by the system. The problem in such models with a large amount of states is the decrease of model transparency. Errors in models with a low transparency are not easily detected.

A formalism that among other things can describe software systems is Graph Transformation. The system states are represented by graphs and the transitions between the states are accomplished by applying graph change rules to those graphs. These rules can be expressed as graphs themselves. A graph transformation model of a software system is therefore a collection of graphs, each a visual representation of one aspect of the system. This formalism may therefore provide a more intuitive approach to system modelling. Graph Transformation and its potential benefits have been studied since the early '70s. The usage of this computational paradigm is best described by the following quote from Andries et al. [?]: "Graphs are well-known, well-understood, and frequently used means to represent system states, complex objects, diagrams, and networks, like flowcharts, entity-relationship diagrams, Petri nets, and many more. Rules have proved to be extremely useful for describing computations by local transformations: Arithmetic, syntactic, and deduction rules are well-known examples." An informative paper on graph transformations is written by Heckel et al. [?]. A quote from this paper: "Graphs and diagrams provide a simple and powerful approach to a variety of problems that are typical to computer science in general, and software engineering in particular."

1.1.1 Research setup

This report describes the setup of a project where the use of graph grammars in model-based testing is researched. In the introduction the motivation is given for using this type of modelling technique. The goal is to create a system for automatic test generation on graph grammars. If the assumptions that graph grammars provide a more intuitive modelling and testing process hold, this new testing approach will lead to a more efficient testing process and fewer incorrect models. The system design, once implemented and validated, provides a valuable contribution to the testing paradigm.

Tools that perform statespace exploration on graph grammars and tools for automatic test generation already exist. Two of these tools will be used to perform these functions. The graph transformation tool GROOVE[1] will be used to model and explore the graph grammar. The testing tool developed by Axini[2] is used for the automatic test generation on *symbolic* models, which combine a state and data type oriented approach. This tool will be referred to in this report as Axini Test Manager (ATM).

1.1.2 Research questions

The research questions are split into a design and validation component:

1. **Design**: How can automatic test generation be done using graph transformation systems? In particular, how can ATM be used together with GROOVE to achieve this?
2. **Validation**: What are the strengths and weaknesses of using graph transformation systems in model-based testing?

The result of the design question will be one system which incorporates ATM and GROOVE. This system will be referred to as the GROOVE-Axini Testing System (GRATiS). In order to answer the first research question sufficiently, GRATiS should produce tests on the basis of a graph grammar and give correct verdicts whether the system contains errors or not.

The criteria used to assess the strengths and weaknesses are split into two parts: the objective and the subjective criteria. The objective criteria are the measurements that can be done on GRATiS, such as speed and statespace size. The subjective criteria are related to how easy graph transformation models are to use and maintain. The assessment of the latter criteria requires a human component. The criteria and methods for the assessment are elaborated in section **??**.

GRATiS will be validated using case-studies. These case-studies are done with existing specifications from systems tested by Axini. Each case-study will have a graph grammar and a symbolic model which describe the same system. GRATiS and ATM are used for the automatic test generation on these models respectively. Both the model and the test process will then be compared as part of the validation. This includes the criteria mentioned in this section. This is explained in more detail in section **??**.

1.1.3 Structure of the report

The structure of this document is as follows: the general model-based testing process is set out in section 1.2. Some basic concepts from first order logic are described in section **??**, used as a framework for dealing with data in the symbolic models used in ATM. These models are then described in section **??**. Section **??** describes graph grammars used in GROOVE. GROOVE and ATM are described in section **??**. The method used to answer the research questions above is in section **??**. Finally, the planning for the project is in appendix **??**.

1.2 Model-based Testing

Model-based testing is a testing technique where a System Under Test (SUT) is tested for conformance to a model description of the system. The general setup for this process is depicted in

[1] http://sourceforge.net/projects/groove/
[2] http://www.axini.nl/

Figure ??. The specification of a system, given as a model, is given to a test derivation component which generates test cases. These test cases are passed to a component that executes the test cases on the SUT. Tests are executed by providing input/stimuli to the SUT and monitoring the output/response. The test execution component evaluates the test cases, the stimuli and the responses. It gives a 'pass' or 'fail' verdict whether the SUT conforms to the specification or not respectively.

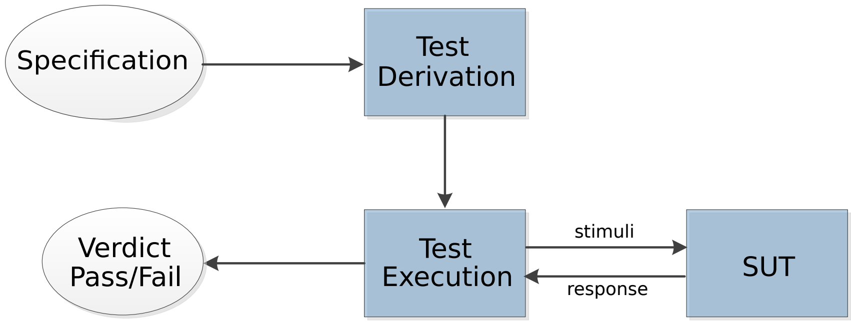


Figure 1.1: A general model-based testing setup

This type of model-based testing is called *batch testing* or *offline testing*. Another type of model-based testing is *on the fly* testing. The main difference is that no test cases are derived, instead a transition in the model is chosen and tested on the system directly. The general architecture for this process is shown in Figure ??. A tool for on-the-fly testing is TorX [?], which integrates automatic test generation, test execution, and test analysis. A version of this tool written in Java under continuous development is JTorX [?].

Variations of state machines and transition systems have been widely used as the underlying model for test generation. Other tools use the structure of data types to generate test data. First, previous work on model-based testing is given. Then, two types of models are introduced. These are basic formalisms useful to understand the models in the rest of the paper. Finally, the notion of *coverage* is explained.

1.2.1 Previous work

Formal testing theory was introduced by De Nicola et al. [?]. The input-output behavior of processes is investigated by series of tests. Two processes are considered equivalent if they pass exactly the same set of tests. This testing theory was first used in algorithms for automatic test generation by Brinksma [?]. This led to the so-called *canonical tester* theory. Tretmans gives a formal approach to protocol conformance testing (whether a protocol conforms to its specifications) in [?] and an algorithm for deriving a sound and exhaustive test suite from a specification in [?]. A good overview of model-based testing theory and past research is given in "Model-Based Testing of Reactive Systems" [?].

1.2.2 Labelled Transition Systems

A labelled transition system is a structure consisting of states with labelled transitions between them.

Definition 1.2.1. A labelled transition system is a 4-tuple $\langle Q, L, T, q0 \rangle$, where:

- Q is a finite, non-empty set of states
- L is a finite set of labels

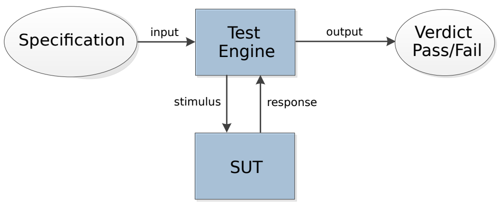


Figure 1.2: A general 'on-the-fly' model-based testing setup

- $T \in Q \times (L \cup \{\tau\}) \times Q$, with $\tau \notin L$, is the transition relation
- $q0 \in Q$ is the initial state.

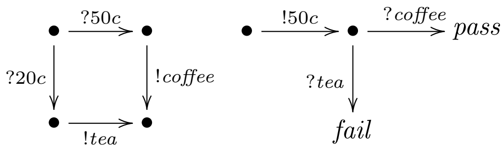
We write $q \xrightarrow{\mu} q'$ if there is a transition labelled μ from state q to state q', i.e., $(q, \mu, q') \in T$. The informal idea of such a transition is that when the system is in state q it may perform action μ, and go to state q'.

1.2.3 Input-Output Transition Systems

A useful type of transition system for model-based testing is the Input-Output Transition System (IOTS) by Tretmans [**?**]. Assuming that implementations communicate with their environment via inputs and outputs, this formalism is useful for describing system behavior. IOTSs have the same definition as LTSs with one addition: each label $l \in L$ has a type $t \in T$, where $T = \{input, output\}$. Each label can therefore specify whether the action represented by the label is a possible input or an expected output of the system under test.

An example of such an IOTS is shown in Figure **??**. This system allows an input of 20 or 50 cents and then outputs tea or coffee accordingly. The inputs are preceded by a question mark, the outputs are preceded by an exclamation mark. This system is a specification of a coffee machine. A test case can also be described by an IOTS with special pass and fail states. A test case for the coffee machine is given in Figure **??**. The test case shows that when an input of '50c' is done, an output of 'coffee' is expected from the tested system, as this results in a 'pass' verdict. When the system responds with 'tea', the test case results in a 'fail' verdict. The pass and fail verdicts are two special states in the test case, which are sink states, i.e., once in either of those the test case cannot leave that state.

Test cases should always reach a pass or fail state within finite time. This requirement ensures that the testing process halts.



(a) An IOTS (b) An IOTS test case

Figure 1.3: The specification of a coffee machine and a test case as an IOTS

1.2.4 Coverage

The number of tests that can be generated from a model is potentially infinite. Therefore, there must be a test selection strategy to maximize the quality of the tests while minimizing the time spent testing. Coverage statistics help with test selection. Such statistics indicate how much of the SUT is tested. When the SUT is a black-box, typical coverage metrics are state and transition coverage of the model [**?**, **?**, **?**].

As an example, let us calculate the coverage metrics of the IOTS test case example in **??**. The test case tests one path through the specification and passes through 3 out of 4 states and 2 out of 4 transitions. The state coverage is therefore 75% and the transition coverage is 50%.

Coverage statistics are calculated to indicate how adequately the testing has been performed [**?**]. These statisics are therefore useful metrics for communicating how much of a system is tested.

1.3 First Order Logic

Some basic concepts from first order logic are described here, used in the definitions of section **??**. For a general introduction into logic we refer to [**?**].

Let $\mathcal{V}$ be a set of *variables*. *Terms* over V, denoted $\mathcal{T}(V)$, are built from a set of function symbols F and variables $V \subset \mathcal{V}$. Each $f \in F$ has a corresponding arity $n \in \mathbb{N}$. if $n = 0$ we call f a constant. We write $var(t)$ to denote the set of variables appearing in a term t. Terms $t \in \mathcal{T}(\emptyset)$ are called ground terms.

A *term-mapping* is a function $\sigma : \mathcal{V} \mapsto \mathcal{T}(\mathcal{V})$. For sets V, W with $V \cup W \subset \mathcal{V}$, we write $\mathcal{T}(W)^X$ for the set of term-mappings that assign to each variable $v \in V$ a term $t \in \mathcal{T}(W)$, and to each variable $v \notin V$ the term v.

A *valuation* ν is a function $\nu : \mathcal{V} \mapsto \mathcal{U}$, where $\mathcal{U}$ is a non-empty set called a *universe*. An example of a universe is $\mathbb{N}$, the non-zero integers. Additionally, $\nu : n - tuple : x \mapsto n - tuple : y$, maps the values of tuple x to the values of tuple y.

An *evaluation* of $\mathcal{T}(\mathcal{V})$ is given by $\epsilon : (\mathcal{T}(\mathcal{V}), \nu : \mathcal{V}) \mapsto \mathcal{U}$. An evaluation $\epsilon : \mathcal{T}(\mathcal{V}), \nu_{before} : \mathcal{V})$ of the terms in a term-mapping results in a set $X \subseteq \mathcal{U}$. A new valuation can then be constructed by: $\nu_{after} : \mathcal{V} \mapsto X$.

1.4 Symbolic Transition Systems

Symbolic Transition Systems (STSs) combine a state oriented and data type oriented approach. These systems are used in practice in ATM and will therefore be part of GRATiS. First, previous work on STSs is given. The definition of STSs and IOSTSs follow. An example of an IOSTS is then given. Next, the transformation of an STS to an LTS is explained and illustrated by an example. This transformation is useful when comparing STSs to systems that are not STSs. Finally, different coverage metrics on STSs are explained.

1.4.1 Previous work

STSs are introduced by Frantzen et al. [?]. This paper includes a detailed definition, on which the definition in section **??** is based. The authors also give a sound and complete test derivation algorithm from specifications expressed as STSs. Deriving tests from a symbolic specification or *Symbolic test generation* is introduced by Rusu et al. [?]. Here, the authors use *Input-Output Symbolic Transition Systems* (IOSTSs). These systems are very similar to the STSs in [?]. However, the definition of IOSTSs we will use in this report is based on the STSs by [?]. A tool that generates tests based on symbolic specification is the STG tool, described in Clarke et al. [?].

1.4.2 Definition

An STS has *locations* and *switch relations*. If the STS represents a model of a software system, a location in the STS represents a state of the system, not including data values. A switch relation defines the transition from one location to another. The *location variables* are a representation of the data values in the system. A switch relation has a *gate*, which is a label representating the execution steps of the system. Gates have *interaction variables*, which represent some input or output data value. Switch relations also have *guards* and *update mappings*. A guard is a term t, where any evaluation on t with any valuation results in a value from $\mathbb{B} = \{true, false\}$. Such a term is denoted by $\mathcal{F}(\mathcal{V})$. The guard disallows using the switch relation when the evaluation of the term results in $false$. When the evaluation results in $true$, the switch relation of the guard is *enabled*. An update mapping is a term-mapping of location variables. After the system switches to a new location, the variables in the update mapping will have the value corresponding to the evaluation of the term they map to.

Definition 1.4.1. A Symbolic Transition System is a tuple $\langle L, l_0, \mathcal{L}, \imath, \mathcal{I}, \Lambda, \rightarrow \rangle$, where:

- L is a finite set of locations and $l_0 \in L$ is the initial location.
- $\mathcal{L}$ is a finite set of location variables.
- $\imath$ is a term-mapping $\mathcal{L} \rightarrow \mathcal{T}(\emptyset)$, representing the initialisation of the location variables.
- $\mathcal{I}$ is a set of interaction variables, disjoint from $\mathcal{L}$.
- Λ is a finite set of gates. The unobservable gate is denoted $\tau (\tau \notin \Lambda)$; we write Λ_τ for $\Lambda \cup \{\tau\}$. The arity of a gate $\lambda \in \Lambda_\tau$, denoted $arity(\lambda)$, is a natural number. The parameters of a gate

$\lambda \in \Lambda_\tau$, denoted $param(\lambda)$, are a tuple of length $arity(\lambda)$ of distinct interaction variables. We fix $\text{arity}(\tau) = 0$, i.e. the unobservable gate has no interaction variables.

- $\rightarrow \subseteq L \times \Lambda_\tau \times \mathcal{F}(\mathcal{V} \cup \mathcal{I}) \times \mathcal{L} \mapsto \mathcal{T}(\mathcal{L} \cup \mathcal{I}) \times L$, is the switch relation. We write $l \xrightarrow{\lambda,\phi,\rho} l'$ instead of $(l, \lambda, \phi, \rho, l') \in \rightarrow$, where ϕ is referred to as the guard and ρ as the update mapping. We require $var(\phi) \cup var(\rho) \subseteq \mathcal{V} \cup param(\lambda)$, where var is the collection of the variables used in the given guard or update mapping.

An IOSTS can now easily be defined. The same difference between LTSs and IOTSs applies, namely each gate in an IOSTS has a type $t \in T$, where $T = \{input, output\}$. As with IOSTSs, each gate is preceded by a '?' or '!' to indicate whether it is an input or an output respectively.

1.4.3 Example

In Figure **??** the IOSTS of a simple board game is shown, where two players consecutively throw a die and move along four squares. The 'init' switch relation is a graphical representation of the variable initialization $\imath$. The defining tuple of the IOSTS is:

$\langle\{throw, move\}, throw, \{T, P, D\}, \{T \mapsto 0, P \mapsto [0,2], D \mapsto 0\}, \{d, p, l\}, \{?throw, !move\},$
$\{throw \xrightarrow{?throw,1<=d<=6,D\mapsto d} move, move \xrightarrow{!move,T=p\wedge l=(P[p]+D)\%4,P[p]\mapsto l,T\mapsto p\%2} throw\}\rangle$

The variables T, P and D are the location variables symbolizing the player's turn, the positions of the players and the number of the die thrown respectively. The output gate $!move$ has $param = \langle p, l\rangle$ symbolizing which player moves to which location. The input gate $?throw$ has $param = \langle d\rangle$ symbolizing which number is thrown by the die. The switch relation with gate $?throw$ has the restriction that the number of the die thrown is between one and six and the update sets the location variable D to the value of interaction variable d. The switch relations with gate $!move$ have the restriction that it must be the turn of the player moving and that the new location of the player is the number of steps ahead as thrown by the die. The update mapping sets the location of the player to the correct value and passes the turn to the next player. In Figure **??** the gates, guards and updates are separated by pipe symbols '|' respectively.

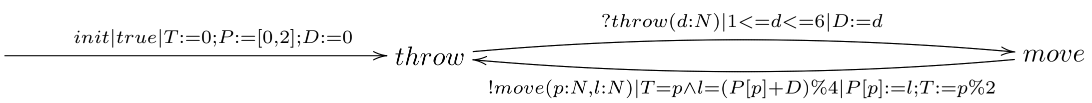


Figure 1.4: The STS of a board game example

1.4.4 STS to LTS transformation

Consider an STS S and its transformation LTS L. The following defines a mapping between $\mathcal{L}$, $\mathcal{V}$, $\mathcal{I}$ and $\rightarrow$ of S to the states Q and transitions T of L.

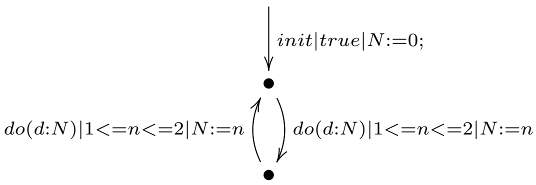
Definition 1.4.2.

$\mu_l : (l \in L, \nu : \mathcal{V}) \mapsto q \in Q$

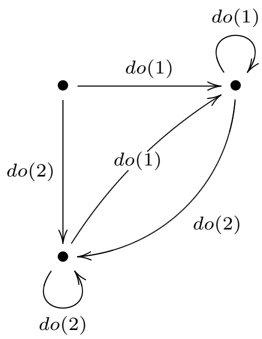
$\mu_r : (r \in \rightarrow, \nu : \mathcal{I}) \mapsto t \in T$

Finding the topology of L is the next step of the transformation. For a switch relation r from location A to location B, a valuation of the location variables ν_l and interaction variables ν_i, $\mu_l : (A, \nu_l)$ maps to a state q, where q is the source state of a transition t, if the result of the evaluation $\epsilon : (\phi \text{ of } r, \nu_l \cup \nu_i)$ is true. ν_{l-new} is the new valuation of the location variables constructed by the evaluation of ρ of r. Then, the target state q' of t is the state mapped by $\mu_l : (B, \nu_{l-new})$. The label of t is a textual representation of λ of r and ν_i. Applying this rule for the topology to all locations, switch relations and concrete values for the variables, results in L. The start state $q0$ of L is the state mapped by $\mu_l : (l_0, \imath)$. All states not reachable from $q0$ are removed from L. When the number of possible valuations for $\mathcal{L}$ and $\mathcal{I}$ and the number of locations in an STS is considered to be finite, the transformation is always possible to an LTS with finite number of states.

An example of this transformation is shown in Figure **??**. The label 'do(1)' in the LTS is a textual representation of the gate 'do' plus a valuation of the interaction variable 'd'. The transformation of a switch relation and concrete values to a transition is also called *instantiating* the switch relation. Another term we will use for a switch relation with a set of concrete data values is an *instantiated switch relation*.



(a) The STS



(b) The LTS

Figure 1.5: An example of a transformation of an STS to an LTS

1.4.5 Coverage

The simplest metric to describe the coverage of an STS is the location and switch-relation coverage, which express the percentage of locations and switch relations tested in the test run. Measuring state and transition coverage of an STS is possible using the LTS resulting from the STS transformation. However, this metric is not always useful, because the number of states and transitions in the LTS depend on the number of unique combinations of concrete values of the variables in the STS. This is potentially very large. For example, when the guards of the switch relations in Figure **??** are removed, the transformation leads to an LTS with a state and transition for each possible value of an integer. It is often unfeasable to test every data value in the STS. The most interesting data values to test can be found by *boundary-value analysis* and *equivalence partitioning*. For an explanation of these terms we refer to [**?**]. Boundary-value analysis was found to be most effective by Reid [**?**] in fault detection.

Data coverage expresses the percentage of data tested in the test run, considering data to be similar if located in the same partition and a better representative of the partition if located close to the partition boundary. These properties of the tested data affect the data coverage percentage.

1.5 Graph Transformation

A *graph grammar* is composed of a start graph and a set of transformation rules. The start graph describes the system in its initial state. The transformation rules describe what changes are made to the graph, resulting in a new graph which describes the system in its new state. The definition is as follows.

Definition 1.5.1. A graph grammar is a tuple $\langle G, R \rangle$, where:

- G is the start graph
- R is a set of graph transformation rules

The rest of this section is ordered as follows: first, graphs and graph morphisms are explained. This is then used to explain graph transformation rules, followed by the definition of a graph grammar. Then, the definition of a *Graph Transition System* (GTS) is given. An example of a graph grammar and a GTS is then given. Finally, a method for transforming a GTS to an STS is given. For a more detailed overview of graph grammars, we refer to [**?**, **?**, **?**].

1.5.1 Graphs & morphisms

Definition 1.5.2. A graph is a tuple $\langle L, N, E \rangle$, where:

- L is a set of labels
- N is a set of nodes, where each $n \in N$ has a label $l \in L$
- E is a set of edges, where each $e \in E$ has a label $l \in L$ and nodes $source, target \in N$

A graph H has an *occurrence* in a graph G, denoted by $H \to G$, if there is a mapping from the nodes and the edges of H to the nodes and the edges of G respectively. Such a mapping is called a *morphism*. An element e in graph H is then said to have an *image* in graph G and e is a *pre-image* of the image. A graph H has a partial morphism to a graph G if there are elements in H without an image in G.

1.5.2 Graph transformation rules

Definition 1.5.3. A transformation rule is a tuple $\langle LHS, NAC, RHS, M \rangle$, where:

- LHS is a graph representing the left-hand side of the rule
- NAC is a set of graphs representing the negative application conditions
- RHS is a graph representing the right-hand side of the rule
- M_{RHS} is a partial morphism of LHS to RHS
- M_{NAC} are partial morphisms of LHS to each $n \in NAC$

A rule R is applicable on a graph G if its LHS has an occurrence in G and $/existsn \in NAC$ such that n has an occurence in G and $\forall e \in LHS$, if e has an image i in n and an image j in G, then j should be an image of j. After the rule application, all elements in LHS not part of M_{RHS}, i.e. they do not have an image in RHS, are removed from G and all elements in RHS not part of M_{RHS}, i.e. they do not have a pre-image in LHS, are added to G.

1.5.3 Graph Transition Systems

By repeatedly applying graph transformation rules to the start graph and all its consecutive graphs, a graph grammar can be explored to reveal a *Graph Transition System* (GTS). This transition system consists of *graph states* connected by *rule transitions*.
Definition 1.5.4. A graph transition system is an 8-tuple $\langle S, L, T, G, R, M_G, M_R, s0 \rangle$, where:

- S is a finite, non-empty set of graph states
- L is a finite set of labels. For each label $l \in L$, the arity of l, denoted $arity(l)$, is a natural number. The parameters of l, denoted $param(l)$, is a tuple of length $arity(l)$ of variables.

- $T \in S \times (L \cup \{\tau\}) \times S$, with $\tau \notin L$, is the rule transition relation. The parameters of a transition $t \in T$ with label $l \in L$, denoted $param(t)$, is a tuple of length $arity(l)$ of constants, such that $\Sigma : param(l) \mapsto param(t)$ is the valuation of the variables of the label.
- G is a set of graphs.
- R is a set of rules.
- M_G is a mapping $\forall s \in S.s \mapsto g \in G \wedge \nexists s' \in S.s \neq s' \wedge s' \mapsto g \in M_G$
- M_R is a mapping $\forall t \in T.t \mapsto r \in R \wedge \nexists t' \in T.t \neq t' \wedge t' \mapsto r \in M_R$
- $s0 \in s$ is the initial graph state.

We write $s \xrightarrow{\mu} s'$ if there is a rule transition labelled μ from state s to state s', i.e., $(s, \mu, s') \in T$.

These systems are very similar to LTSs. A GTS can be transformed to an LTS by omitting the graphs, rules, mappings and parameters on labels.

1.5.4 Example

Figure **??** shows an example of the start graph and one rule of a graph grammar. M_{RHS} maps the A and B nodes in LHS to the A and B nodes in RHS respectively. M_{NAC} maps the A node in LHS to the A node in both graphs in NAC. The a-edge in LHS is mapped to the a-edge in the first NAC. The LHS of the rule has an occurrence in the start graph, as the A and B node connected by the a-edge exists in both graphs. None of the graphs in the NAC have an occurrence in the start graph, because the C node does not exist in the start graph. The new graph after applying the rule is in Figure **??**.

$\boxed{\text{A}} \xrightarrow{a} \boxed{\text{B}}$

(a) The start graph

$\boxed{\text{A}} \xrightarrow{a} \boxed{\text{B}}$

(b) The LHS

$\boxed{\text{A}} \xrightarrow{a} \boxed{\text{C}}$

(c) The first NAC

$\boxed{\text{A}} \xrightarrow{b} \boxed{\text{C}}$

(d) The second NAC

$\boxed{\text{A}} \xrightarrow{b} \boxed{\text{B}}$

(e) The RHS

$\boxed{\text{A}} \xrightarrow{b} \boxed{\text{B}}$

(f) The result

Figure 1.6: An example of a graph grammar

1.5.5 GTS to STS transformation

The method described here transforms a GTS to an STS. This STS is not *optimal*, i.e. it is reducible to an STS with fewer locations and switch relations. This method only serves as a proof used in section **??**.

For each graph state $s \in S$ create a location $l \in L$. The start location $l_0 \in L$ is the location created by the state $s0 \in S$. Set $\mathcal{V} = \emptyset$ and $\imath = \emptyset$. For each label $l \in L$ create a gate $\lambda \in \Lambda$. For each $p \in param(l)$ create an interaction variable $i \in \mathcal{I}$ of the same type as p and add i to $param(\lambda)$. Set $arity(\lambda) = arity(l)$. For each rule transition $t \in T$ create a switch relation $r \in \rightarrow$, where:

- the source and the target locations of r are the locations created by the source and target graph states of the rule transition.
- the gate of r is the gate created by the label on the transition.

- for each $p \in param(l)$ and $i \in \mathcal{I}$ created by p create an $i = p$ expression. The guard of r is those expressions joined by the $\wedge$ operator.
- the update mapping of r is empty.

An example of such a transformation is done using the LTS in Figure ??. Consider this LTS to be a GTS where the states are graph states, the transitions are rule transitions with label 'do' with $arity(do) = 1$ and $param(do)$ the integers between brackets are The STS resulting from the transformation is in Figure ??.

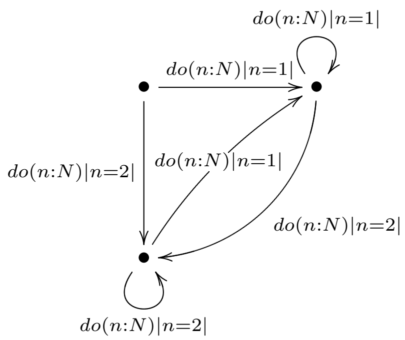


Figure 1.7: The basic STS resulting from the transformation of the LTS in Figure ??

1.6 Tooling

1.6.1 ATM

ATM is a web-based model-based testing application, developed in the Ruby on Rails framework. It is used to test the software of several big companies in the Netherlands since 2006. It is under continuous development by Axini.

The architecture is shown graphically in Figure ??. It has a similar structure to the on-the-fly model-based testing tool architecture in Figure ??.

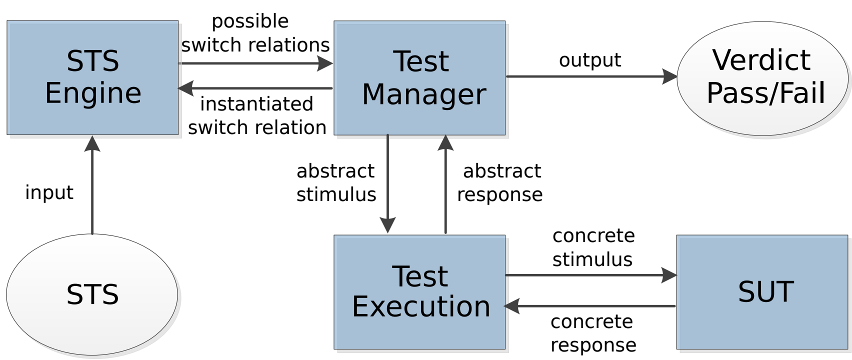


Figure 1.8: Architecture of ATM

The tool functions as follows:

1. An STS is given to an STS Engine, which keeps track of the current location and data values. It passes the possible switch relations from the current location to the Test Manager.

2. The Test Manager chooses an enabled switch relation based on a test strategy, which can be a random strategy or a strategy designed to obtain a high location/switch relation coverage. The valuation of the variables in the guard are also chosen by a test strategy, which can be a random strategy or a strategy using boundary-value analysis. The choice is represented by an instantiated switch relation and passed back to the STS Engine, which updates its current location and data values. The communication between these two components is done by method calls.

3. The gate of the instantiated switch relation is given to the Test Execution component as an *abstract stimulus*. The term abstract indicates that the instantiated switch relation is an abstract representation of some computation steps taken in the SUT. For instance, a transition with label 'connect?' is an abstract stimulus of the actual setup of a TCP connection between two distributed components of the SUT.

4. The translation of an abstract stimulus to a concrete stimulus is done by the Test Execution component. This component provides the stimulus to the SUT. When the SUT responds, the Test Execution component translates this response to an abstract response. For instance, the Test Execution component receives an HTTP response that the TCP connect was succesful. This is a concrete response, which the Test Execution component translates to an abstract response, such as a transition with label 'ok!'. The Test Manager is notified with this abstract response.

5. The Test Manager translates the abstract response to an instantiated switch relation and updates the STS Engine. If this is possible according to the model, the Test Manager gives a pass verdict for this test. Otherwise, the result is a fail verdict.

1.6.2 GROOVE

GROOVE is an open source, graph-based modelling tool in development at the University of Twente since 2004 [?]. It has been applied to several case studies, such as model transformations and security and leader election protocols [?].

The architecture of the GROOVE tool is shown graphically in Figure ??. A graph grammar is given as input to the Rule Applier component, which determines the possible rule transitions. An Exploration Strategy can be started or the user can explore the states manually using the GUI. These components request the possible rule transitions and respond with the chosen rule transition (based on the exploration strategy or the user input). The Exploration Strategy can do an exhaustive search, resulting in a GTS. The graph states and rule transitions in this GTS can then be inspected using the GUI.

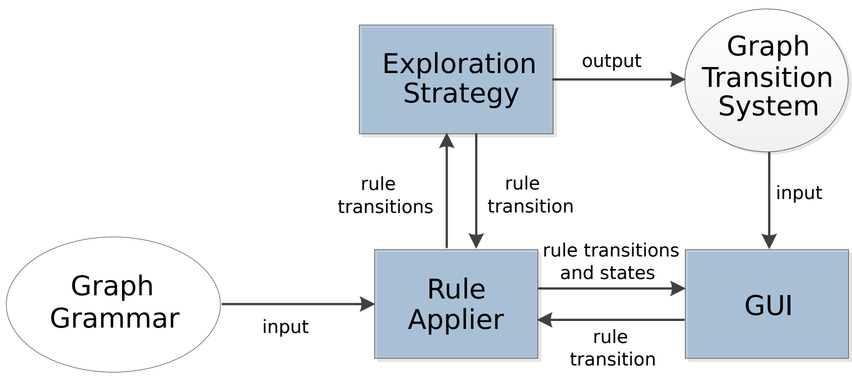


Figure 1.9: The GROOVE Tool

1.6.3 GROOVE example

The *LHS*, *RHS* and *NAC* of a rule in graph transformation tools, such as GROOVE, are often visualized together in one graph. The running example from Figure **??** is displayed as a graph grammar, as visualized in GROOVE, in Figure **??**. Figure **??** is the start graph of the system.

The colors on the nodes and edges in the rules represent whether they belong to the *LHS*, *RHS* or *NAC* of the rule.

1. normal line (black): This node or edge is part of both the *LHS* and *RHS*.
2. dotted line (red): This node or edge is part of the *NAC* only.
3. thick line (green): This node or edge is part of the *RHS* only.
4. dashed line (blue): This node or edge is part of the *LHS* only.

The rules can be described as follows:

1. **??**: 'if a player has the turn and he has not thrown the die yet, he may do so.'
2. **??**: 'if a player has the turn and he has thrown the die and this number is larger than zero, he may move one place and then it is as if he has thrown one less.'
3. **??**: 'if a player has finished moving (number thrown is zero), the next player receives the turn.'

The *turn* flag on the **Player** node is a representation of a self-edge with label *turn*. The assignments on the **Die** node are representations of edges to integer nodes. The throws value assignment (:=) in the move rule is a shorthand for two edges: one edge in the *LHS* with label *throws* from the **Player** node to an integer node with value i and another edge in the *RHS* with label *throws* from the **Player** node to an integer node with value $i-1$. In the next turn rule, the *turn* edge exists in the *LHS* as a self-edge of the left **Player** node and in the *RHS* as a self-edge of the right **Player** node. In the same rule, the *throws* edge from the left **Player** node to an integer node only exists in the *LHS*. The number '0' in the top left of the **int** node in the throw rule indicates that this integer is the first parameter in $param(l)$, where l is the label on the rule transition created by applying the throws rule.

The graph is transformed after the rule is applied. The resulting graph after the transformation is the new state of the system and the rule is the transition from the old state (the graph as it was before the rule was applied) to the new state. Figure **??** shows the GTS of one *throws* rule application on the start graph. The number on the label is the *parameter* of the label. State s_1 is a representation of the graph in Figure **??**. Figure **??** shows the graph represented by s_2.

1.6.4 Comparison of the examples

The models of the boardgame example in Figures **??** and **??** are very different. In this section the STS and the graph grammar of the example are compared.

Comparison of behavior

The GTS of the graph grammar of the boardgame example has a number of consecutive transitions when a player moves. The *move* rule puts the **Player** on the next **Location** and lowers the remaining 'moves' by one. This is different from the STS, which updates the location variable in one transition. The effect is that the behavior of both systems is different; one specifies the movement of a **Player** as: "Player p moves to Location l", the other as: "The Player with the turn moves to the next Location". Which behavior is required when this boardgame would be tested

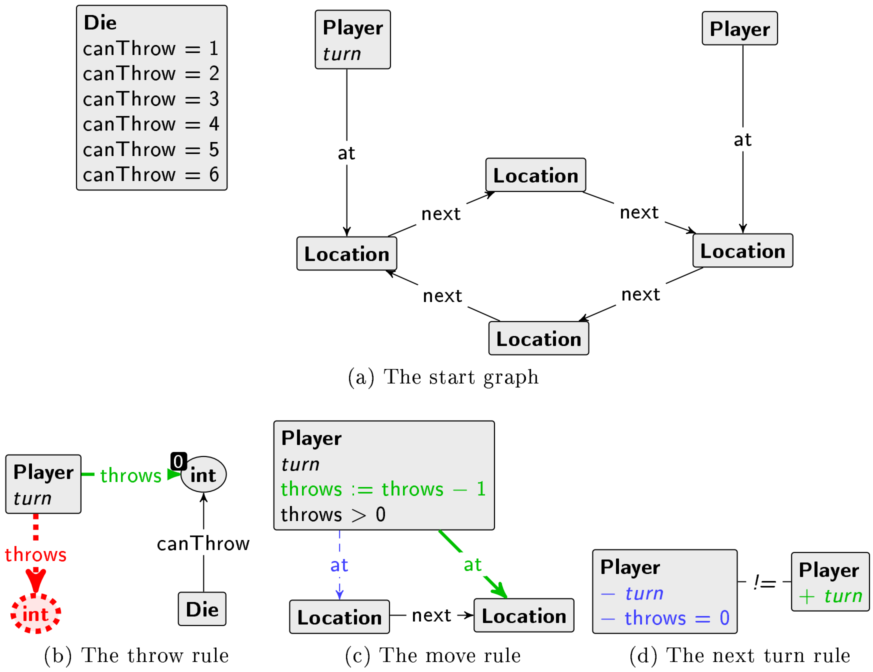


Figure 1.10: The graph grammar of the board game example in Figure ??

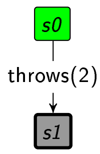


Figure 1.11: The GTS after one rule application on the board game example in Figure ??

depends on the implementation of the game. However, to show the power of the GTS formalism, Figure ?? shows the graph grammar with the same behavior as the STS. It models the location as a variable and updates this variable in one transition. It also identifies the **Players** by giving them a number.

The new graph grammar loses many advantages by structuring it in this way: the overview of the board is gone, the rules are less visual and extending the locations in different directions is much harder. On the other hand, there are fewer rules and the graphs are more compact. However, when finding the GTS corresponding to this graph grammar, the labels of the transitions of that GTS do not reflect the 'move(p:N, l:N)' label of the STS. This should be done by marking the correct nodes as described in section ??. The problem is that the result of the equation in the 'move' rule is only derived when the rule is applied. Figure ?? shows a rule where the equation is shown graphically. The die roll, connected by the 'throws' edge, and the number of the **Location** the **Player** is at are added. The result is represented by the **int** node connected by the 'add' edge. This result modulo 4 is represented by the **int** node connected by the 'mod' edge. This node is marked as the second parameter, the number of the **Player** is marked as the first parameter. This labels the transitions with which player moves to which location.

Comparison of Transition Systems

The GTS of a graph grammar can be computed using GROOVE and the STS can be transformed to an LTS. The two graph grammars and the STS of the board game example result in three

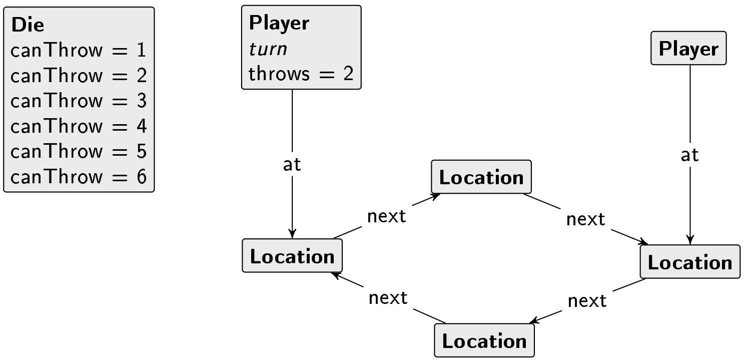
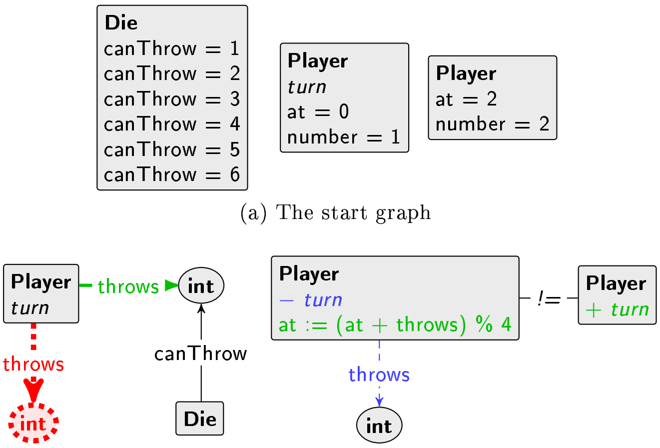


Figure 1.12: The graph of state $s2$ in Figure ??



(a) The start graph

(b) The throw rule

(c) The move rule

Figure 1.13: Another graph grammar of the board game example

transition systems which can be compared.

The graph grammar from Figure ?? generates a GTS with 32 states with 52 transitions, which can be seen visually in Figure ??. The graph grammar from Figure ??, using the 'move' rule from Figure ??, generates 224 states with 384 transitions, shown as GTS in Figure ??. The reason of the difference in number of states and transitions is that the board is circular: to the first graph grammar, the players being at locations 1 and 3 is the same as them being at locations 2 and 4. However, this is not the same to the second graph grammar. Also, for the first graph grammar it does not matter which **Player** node is at a **Location** node; they are the same apart from which **Player** has the 'turn'. As an example, consider the start graph in Figure ??. If both players throw a '1' and move to the next location, the state is as shown in Figure ??. Both states are symmetrical and therefore they are the same state. This leads to a *symmetry reduction* of the statespace for the first graph grammar.

The LTS where the STS in Figure ?? is transformed to has 224 states and 384 transitions. This is calculated by taking all possibilities of the data values except for the die roll. This leads to 32 states ($4 \times 4 \times 2$). These 32 'throw' states each have 6 'throw?' transitions to a 'move' state, thus there are 192 'move' states. The 'move' states only have one transition back to a 'throw' state. There are $6 \times 32 + 192 \times 1 = 384$ transitions.

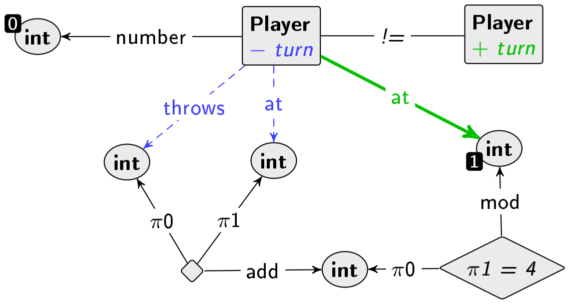


Figure 1.14: An alternative move rule

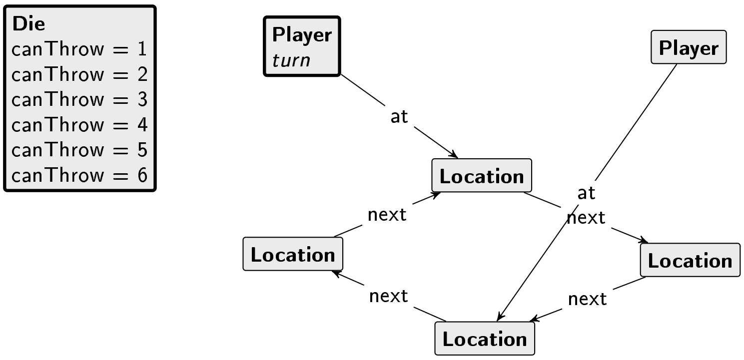


Figure 1.15: An example of a state symmetrical with the state in Figure ??

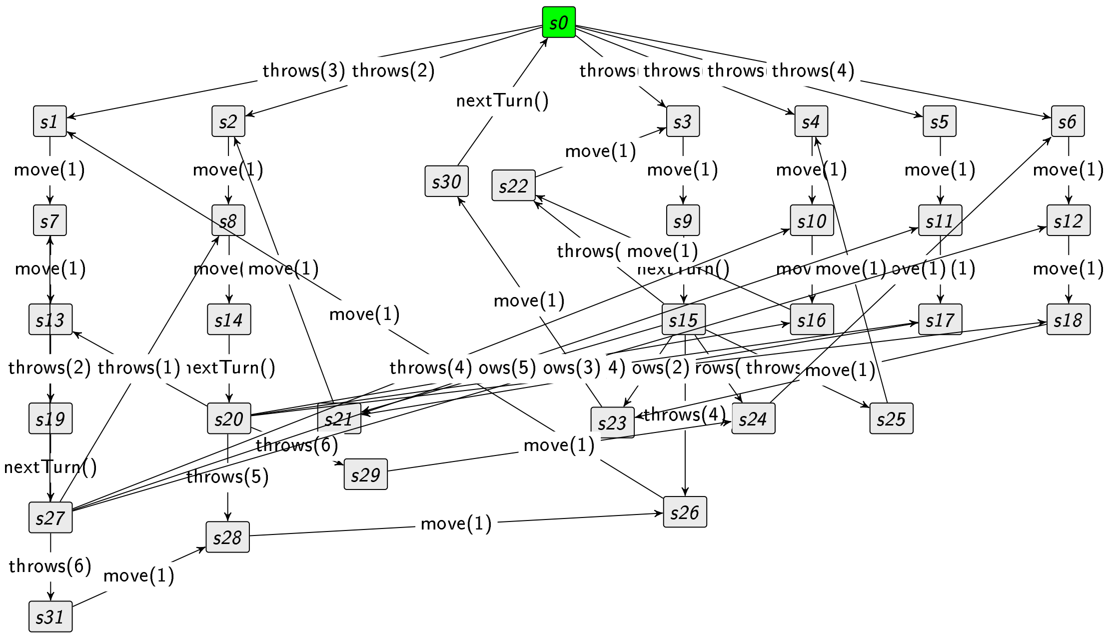


Figure 1.16: The GTS of the model in Figure ??

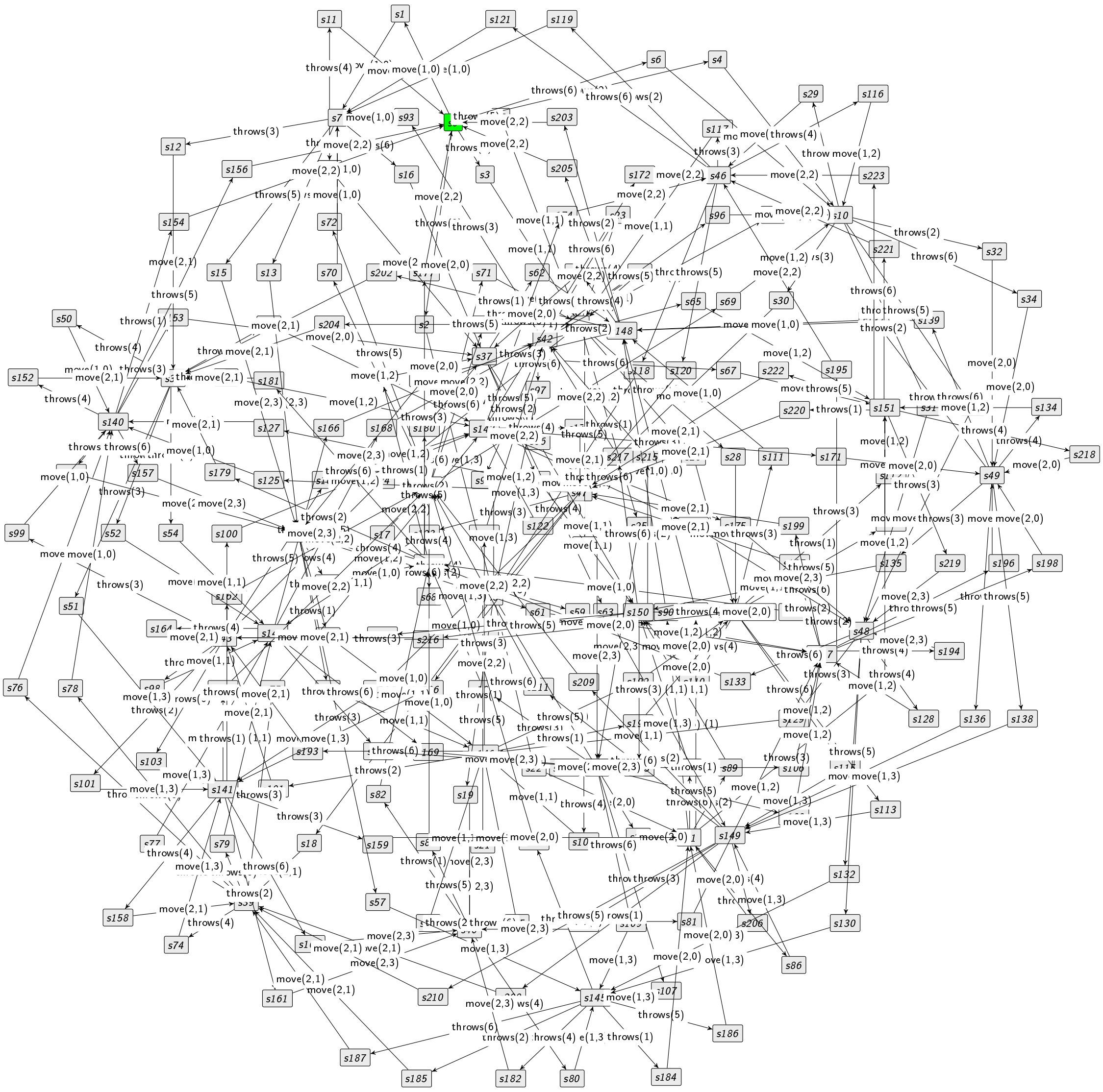


Figure 1.17: The GTS of the model in Figure **??**

Chapter 2

Design

This chapter covers the design issues of GRATiS. The concrete method chosen to construct GRATiS is to transform a graph grammar into an STS in GROOVE and do the model-based testing with that STS in ATM. revise this sentence

Section ?? gives a formal approach to transforming a graph grammar into an STS. Sections ?? through ?? each cover a specific design problem with possible solutions. Section ?? gives two possible implementations of GRATiS with the advantages and disadvantages of each implementation.

2.1 Graph grammar to STS transformation rules

2.1.1 Graph state to location

Generalized graph states.

2.1.2 Rule match to switch relation

Rule transition label to gate.

Variables

Variable node match from rule to graph state is location variable. Parameterized variable nodes are interaction variables.

Rule priority

Add negated guard to switch relations from lower rule priority.

Guard

NAC expressions over variable nodes in lhs are guards.

Update

NAC expressions over variable nodes in rhs are updates.

2.2 Exploration strategy

A GROOVE exploration strategy finds all graph states and rule matches.

Isomorphism

Isomorphism prevents correct tracking of location variables. Solve with sets.

Eraser/creator pairs

Location variables should be persistent and declared at the start state. Therefore, every eraser edge to a variable node should be paired with a creator edge. This edge should have the same source node and label.

2.3 Partial matching

2.3.1 Theory

Generalizing rule matches.

2.3.2 Application

Using partial matching in an exploration strategy, only the generalized graph states and rule matches are found.

2.4 Reachability

2.4.1 Theory

MSc thesis Floor Sietsma "A Case Study in Formal Testing and an Algorithm for Automatic Test Case Generation with Symbolic Transition Systems"

2.4.2 Application

Allows halting an exploration strategy when location no longer reachable. Only works for specific path though.

2.5 Pre-testing vs. on-the-fly transformation

Pre-testing transformation is the process of entirely transforming a model before starting test runs. *On-the-fly* transformation is the process of transforming the needed parts of a model while doing a test run.

Explore entire sts + coverage statistics vs. on the fly exploration and no coverage statistics. Being in multiple places at once. Reachability check in exploration strategy vs. check in on the fly exploration.

Which implementation do we use and why?

Chapter 3

Validation

This chapter covers the validation of the design. The validation is done through case-studies, reported in section **??**. Measurements on the performance are done and reported in section **??**.

Why case-studies?

3.1 Case Studies

3.2 Benchmarks

Chapter 4

Conclusion

4.1 Summary

This report motivates the need of a research towards a model-based testing practice on Graph Transformation Systems. The goal will be to create a tool that allows automatic test generation on GTSs and assess the strengths and weaknesses of this test practice.

The first observations in this report demonstrate that GTSs can provide a nice visiualization of a system. However, the representation of data values and in a GTS were not Increasing the complexity of the software system may change this. The transformation rules, given as separate graphs, provide a good overview of the behavior of the system. This feature should be beneficial in models for larger software systems.

The results also show an interesting automatic statespace reduction, namely the symmetry reduction. The second GTS of the example shows that also a purely arithmetic model can be built; this indicates the strength of the formalism.

The design phase is split into small steps that should break down the complexity of the entire implementation process. The validation with the use of the case studies emphasises the practicality of the tooling; the purpose of the test tools is to be used on real-world software systems. Finally, the experiments are a great indication of the usefulness of the tool towards software testers.

4.2 Conclusion

4.3 Future Work